Renewable and Sustainable Energy Reviews 28 (2013) 474–482

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Valuing Chinese feed-in tariffs program for solar power generation: A real options analysis

Boqiang Lin [a,b,*], Presley K. Wesseh, Jr. [b,c]

[a] New Huadu Business School, Minjiang University, Fuzhou 350108, China
[b] Collaborative Innovation Center for Energy Economics and Energy Policy, China Institute for Studies in Energy Policy, Xiamen University, Xiamen, Fujian, 361005, China
[c] Department of Economics, University of Liberia, Capitol Hill 1000, Monrovia 10, Liberia

ARTICLE INFO

Article history:
Received 4 April 2013
Received in revised form
1 August 2013
Accepted 11 August 2013
Available online 2 September 2013

Keywords:
Renewable energy
Solar PV
Feed-in tariffs
Real option

ABSTRACT

Combustion of coal accounts for about 75% of total power generation in China. The global call for CO_2 emissions reduction, exposure to oil risks and their bearing on energy security, require China to properly determine its future energy policies. This study has attempted to quantify the benefits provided by current Chinese feed-in tariff (FIT) policy for solar power generation by using real option pricing approach to estimate the value of solar energy technologies in the face of uncertain fossil fuel prices and learning effects in solar technologies. The optimal solution as calculated renders the government's FIT effort as a sufficient mechanism to make solar an economically competitive alternative in China's energy future. In addition, options values in terms of internalized external costs and variation in the level of FIT are also compared. Simulation results reveal the options value to be significantly greater when external costs are internalized. Nevertheless, it was found that the average current FIT level is non-optimal, and should be increased to between 1.5 RMB/KWh and 1.7 RMB/KWh to ensure maximum investment incentive with minimal government expenditures. Furthermore, given solar to be an attractive alternative for the future, his study hypothesizes that solar power use in China can potentially reduce CO_2 emissions by approximately 1.3% by 2020 compared to the 2005 level.

Contents

1. Introduction

As the Chinese economy and industrial base grows and expands, demand for power continues to increase at an annual rate of close to 10%. Combustion of coal accounts for about 75% of total power generation. The global clamor for carbon emission reduction couple with threats of 'peak oil', international oil shocks and their bearing on energy security, require China to properly determine its future energy

* Corresponding author at: New Huadu Business School, Minjiang University, Fuzhou 350108, China. Tel.: +86 592 2186076; fax: +86 592 2186075.
E-mail addresses: bqin@xmu.edu.cn (B. Lin), masterpresley@yahoo.com (P.K. Wesseh, Jr.).

1364-0321/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.rser.2013.08.043

policies. As a result, Chinese policy makers and scholars have shown a growing interest in the development of renewable energy (RE) and its substitution for fossil fuels, especially coal and oil. Although affected by many uncertainties, China has rapidly moved along the path of RE development and RE energy has played a major role in helping China meet its rising energy demand, improve its energy structure, reduce environmental pollution, stimulate economic growth, and create job opportunities. In fact, the current Chinese goal calls for 15% of its primary energy from non-fossil fuel by 2020, while producing affordable electricity for residential, industrial and commercial customers. Renewables are expected to be an important part of this target. For, China's solar power installed capacity target was adjusted recently from 5 GW to 35 GW by 2015.

Considering China's available RE resources, the Chinese government has realized that developing solar power is inevitable if the country must achieve its RE target and provide help for Chinese PV manufacturers suffering from international trade protectionism. Solar photovoltaic (PV), with an installed capacity of 3300 MW at the end of 2011 is currently a minor contributor to China′s total power supply. In an effort to boost the domestic solar industry and to increase the share of solar power in China′s energy portfolio, China′s energy regulator, the National Development and Reform Commission (NDRC) announced in July 2011 its first nationwide FiT for solar PV development. With the adoption of an attractive pricing structure, it is expected that the new FiT system will go a long way in stimulating domestic investment in the solar sector and improving the outlook for Chinese PV manufacturers, which already dominate the global market for solar equipment.

Notwithstanding, considering that the FIT policy is likely to face serious challenges, the important questions one may ask then are (1) Is the government FIT effort sufficient to make solar an economically competitive alternative to coal or oil in China′s energy future? (2) If the FIT effort does spur investment in solar technologies, how can one measure the benefits derived from the program? (3) Is the value of the tariff optimal to maximize investment efficiency and address energy security issues and mitigation?

The objective of this study is to therefore estimate the potential for solar as an economically competitive alternative to fossil fuels in China's energy future. To achieve our purpose, this study uses real options framework and builds on the dynamic programming model in [1] which takes into account major factors affecting RE technologies investment. Indeed, the significance of such a study cannot be overemphasized. Due to the importance of energy consumption for growth and development[1] in a rapid developing country like China, improved decision support for a sustainable energy transition is timely. Given China's dependence on coal and imported oil fuels, the economic and environmental savings from R&D and deployment of RE technologies may be substantial. Another very important factor which creates the need for such a study is the fact that some RE programs in China appear not to operate effectively or efficiently [2]. The contribution of this study turns out to be quite remarkable and brings new insights into the literature both in terms of Chinese energy policy as well as the options behavior. The major contributions are: First, this study is the first one to use real options to analyze investment opportunities for power generation in China. The idea of taking a developing-country perspective and attempting to provide insights about the optimal level of funding can present opportunities. Second, the modeling approach adopted in this study more closely represents the actual RE development climate than many previous models that assigned fixed values to technical risk or that considered only a single factor in RE technical improvements. Third, contrary to the referenced paper in which bulk of the value constituted existing RE technologies, in the current study, most of the options value in the base case stems from future policy enhancement. Hence, this brings new insights in terms of options behavior and creates incentives for policy-makers to continue funding. Fourth, the paper puts forward a major conclusion that while solar energy technologies are economically attractive for China's energy future, the current funding level is low. Finally, our paper provides valuable inputs for making sound, informed energy supply and demand choices and developing policy options to address climate change mitigation in China.

The layout of the paper is as follows: Section 2 explains the concept of real options and provides a summary of studies which have applied real options theory to the energy sector. Section 3 describes the modeling approach adopted in this study. Section 4 presents the scenario analysis and parameter estimation. Section 5 concludes.

2. Real options theory and application to the energy sector

The energy sector is marked by a high degree of uncertainty, which is caused by volatility of prices of energies and energy commodities in the international markets as well as by the fact that the investment projects in this sector are time-consuming, large-scale and extremely expensive. In recent years it has increasingly been recognized that in such liberalized markets traditional investment calculations, such as net present value (NPV) and discounted cash flow approaches (DCF) proposed by Fisher [5,6] are inadequate (see [7–10], etc.). More besides, these traditional techniques make implicit assumptions, like the reversibility of investments. In other words, an investment can be undone and the expenditures recovered. On the other hand, if a firm does not undertake the investment now, it will not be able to do it in the future and this will become unrecoverable [11]. This should be a concern since in fact most investments projects might not have these features. As noted by Fernandes et al., [11], the ability to delay an investment, in order to obtain more information and thus reducing uncertainty, provides management with a valuable opportunity to modify both investment and the strategy to follow, in order to get better future opportunities or to reduce future losses. Another drawback of traditional methods is the fact that they cannot promptly reflect flexibility in investment decisions, possibly underestimating the opportunity and actual values of an investment see [12].

Options theory was originally developed in the 1970s by Black and Scholes [13] and Merton [14] to evaluate financial options, but economists realized very soon that option pricing could also provide important insights into decision-making on capital investments. Therefore, with reference to the real assets involved, the term “real options” was established and first used by Myers [15]. According to Myers, profits created by cash flow generated from an investment arise from the use of currently owned assets in addition to an option for future investment opportunities. In contrast to the “now or never” proposition implicit in traditional capital budgeting approaches, real options analysis is a more sophisticated approach that enables to take into account the “value of waiting” that accrues from the irreversibility of an investment (sunk cost), uncertainty, and the flexibility of postponing an investment in order to obtain more information about the future. This flexibility of waiting can be considered as an option that is forfeited when the investment is made. Keeping the option alive, i.e. to maintain the flexibility to invest or not to invest, has a value that can be calculated [16]. In recent years, a number of studies have applied real options theory to decision-making problems in the energy sector. The next paragraphs will provide a

[1] See [3,4] for more perspectives on the importance of energy consumption for growth.

chronological overview of publications that apply real options theory in the context of RE.[2]

A number of authors have focused mainly on the area of power generation. The first study in this area, [17], identified a framework to evaluate RE power projects under uncertainty within a competitive market environment. Drawing from the case of Greece, the authors evaluated a wind energy-to-electricity project according to the real options theory using the Black–Scholes Model. Their findings suggested a positive option value further noting that the uncertain parameters of an investment project include fossil fuel price, environmental regulations, demand, supply, technology, and market structure. Kjaerland [18] applied the real option evaluation framework of Dixit and Pindyck [19] to potential hydropower investments in Norway to quantify the option value and to understand the timing and aggregate investment behavior in this industry. Their approach took into account the uncertainty of fossil fuel price, water reserves, risk-free interest rate, investment cost, variable costs, and the best investment time. In a related research, Bockman et al. [20] developed a real options-based method with continuous scaling for assessing small hydropower projects that are subject to uncertain electricity prices. The authors applied their method to three different Norwegian hydropower projects. Munoz~ et al. [21] present a decision-making tool for investment in wind energy plant using a real options approach. To illustrate their decision-making method which allows wind energy investors to decide whether to invest under different scenarios, they performed several realistic case studies. Martínez-Cesena~ and Mutale [22] proposed an advanced real option methodology for renewable energy generation projects planning, and illustrates the methodology using variations of a hydropower case study. Their results show higher expected profits for projects planned with the advanced real option methodology compared with other methods.

Some strands of studies directly shed light on real options theory in policy evaluation. Yu et al. [23] focused on evaluating the flexibilities associated with switching tariff in Spanish electricity markets. Using the real options framework, they implemented numerical techniques to evaluate switching tariff for different wind generation assets, and to identify optimal switching policies and values. Kumbaroglu et al. [24] later presented a policy planning model that integrates learning curve information on renewable power generation technologies into a dynamic programming formulation featuring real options analysis. The empirical application of their model which was based on data for the Turkish electricity supply industry did not only provide general implications for policy-making, but also suggested some interesting insights about the impact of uncertainty and technical change on the diffusion of various emerging RE technologies. Siddiqui and Fleten [25] examined how a staged commercialization program for an unconventional energy technology could proceed under uncertainty. Drawing on evidence from Taiwan, Lee and Shih [26] presented a policy benefit evaluation model that integrates cost efficiency curve information on renewable power generation technologies into real options analysis methods. Their framework allows assessing volatility, uncertainty, and managerial flexibility in policy planning. Boomsma et al. [27] adopted a real options approach to analyze investment timing and capacity choice for RE projects under the most extensively employed policy schemes, namely, FITs and RE certificate trading. Restricting attention to Norway in a case study based on wind power, the authors found that the FIT encourages earlier investment. Nevertheless, as investment has been undertaken, RE certificate trading creates incentives for larger projects.

Few authors have directed attention to real options theory in R&D investments/programs. The earliest application to renewable energy dates back to Davis and Owens [28]. In order to quantify the benefits provided by continued U.S. federal non-hydro renewable electric R&D, they adopted real options pricing techniques to estimate the value of renewable electric technologies in the face of uncertain fossil fuel prices as well as determine the optimal level of annual federal RE R&D expenditures. Following similar line of research, Siddiqui et al. [1] examined the strategy for RE R&D in the United States. Studying the deterministic approach employed by the Department of Energy and the real options model developed by Davis and Owens [28] they developed a real options model which uses a binomial lattice structure. The authors argued that a binomial lattice reveals the economic intuition underlying the decision-making process, while a numerical example illustrates the option components embedded in a simplified representation of current US Federal RE research, development, demonstration and deployment.

In summary, a main feature of the real options approach is the inclusion of the possibility of delaying an investment and evaluating the value of waiting as part of the decision-making problem, which allows for a much richer analysis than if this aspect is neglected. In addition, it may help to avoid erroneous conclusions from overly simplistic investment modeling, which has been frequently criticized. A review of studies has suggested that several factors may affect the development of RE which include NRE cost, RE cost, RE subsidies which could take the form of R&D expenditures on RE, advancement of RE technology, as well as RE demand.

It is no doubt that the above factors do play a significant role in Chinese RE development. On top of these however, the role of Chinese energy policies cannot be neglected. In light of the literature overview presented, less focus has been placed on solar technologies despite having great prospects for the development of RE all over the world. Most importantly, one may easily observe that the real options theory has never been applied to the valuation of RE policy for power generation in China even though the approach is said to provide attractive opportunity for evaluating investment decision planning since the method is one tool that accurately measures the value of a specific project. Ma et al. [2] conducted a survey of China's RE economy and suggested the need for more comprehensive studies noting that "some RE programs appear not to operate effectively or efficiently".[3] Indeed, a considerable number of studies have described various policy instruments while some even analyze the incentives these policies have created for RE investment in China (e.g. [29,30]). However, these studies fail to quantify the benefits provided by various policy schemes. Hence, this paper steps into this gap by attempting to quantify the benefits provided by continued RE policy for solar power development in China. Therefore, estimating the value of solar energy technologies and attempting to find the optimal FIT policy solution in the face of uncertain fossil fuel prices and learning effects is what the rest of this paper aims to achieve.

3. Model framework

While the costs of many RE systems are largely upfront and therefore stable due to utilization of free fuel, the costs of conventional forms of energy supply are largely associated with fuel costs, which consist of a large portion of their price – in addition making them more expensive from a life-cycle perspective. Fuel prices are subject to fluctuation making conventional sources risky from a cost perspective[4]. Conventional sources of

[2] For the application of real options theory to decision-making problems in the NRE energy sector, interested readers are referred to [11].

[3] See [2] for a review of existing literature on China's renewable energy economy published in "Renewable and Sustainable Energy Review" and "Biomass and Bioenergy".

[4] Example of such volatility of fuel prices is described in [31].

energy have hidden costs which are not reflected through prices. Unfortunately, the high upfront costs of RE systems can be discouraging for many. Nevertheless, indications are that the development of RE could lead to cost savings where in consumers are provided with electricity at a cost lower than that of NRE technologies. Hence, beginning with the consumers cost savings and considering key influential factors mentioned in the literature review, we can model the policy value of developing RE as a real option for energy cost savings. The theoretical platform developed in this paper builds on the model framework of Siddiqui et al. [1]. The model here does not incorporate technical risk; reason being to simplify the initial analysis. As an alternative, the options value of RE development is determined by assuming policy planning success but given market risk i.e., allowing for stochastic NRE costs. Unlike [1], this study not only considers a scenario in which external cost is internalized, but also makes use of learning curves in order to take into consideration the fact that solar energy technologies, due to their greater potential for cost reductions (higher learning rates, less prone to environmental taxation), are expected to successfully compete with conventional technologies at some time in the future [24]. The timing of policy planning flexibility is partially addressed in that the policy maker has the ability to cease policy as conditions warrant.

3.1. Cost uncertainties of non-renewable energy

To begin the option analysis, it is necessary to be more precise about the future uncertainty surrounding NRE and investment costs. Notwithstanding, one must not forget that the prices of NRE have been maintained at a relatively low level by the Chinese government, as evidenced by the common practice of subsidizing fossil fuels. In 2007 for instance, China's end-use fossil fuels subsidies amounted to 356.73 billion RMB; roughly equivalent to 1.43% of GDP. In terms of fuels, oil products subsidies alone amounted to 189.03 billion RMB sharing about 53.0% of total fossil fuels subsidies and 0.76% of GDP [32]. Given these subsidies, it sounds reasonable to expect that energy prices in China do not accurately reflect production costs. In the case where NRE becomes expensive, RE becomes comparatively attractive. However, the uncertainty and volatility of NRE prices may also be viewed as a negative factor in RE development. When NRE is cheaper than RE, the power generation cost of NRE is proportionately smaller. The comparatively higher cost of generating RE makes it even more unattractive whereas high NRE prices increase the competitiveness of RE [26].

Based on a binomial stochastic process, this study simulates the variability of NRE costs with the data providing the basis for developing a valuation model. This may be viewed as the probability of successfully developing RE. We represent the changes in NRE costs as the geometric Brownian motions (GBM), which is in accordance with findings that have been reported in the literature and can be adequately approximated via a multi-period binomial process in which the NRE cost in the next period either increases or decreases from its current level, over a total of T periods. For instance, let $S(k,i)$ represent the uncertainty in NRE cost with k periods elapsed in the RE policy lifetime and i upward cost movements to date. For an initial NRE cost representation of $S(0,0)$, the cost for the next period is stochastic and can take on two values:

$$\begin{cases} S(1,1) = uS(0,0), & \text{with probability} \quad p \\ S(1,0) = dS(0,0), & \text{with probability} \quad 1-p \end{cases}$$

This trajectory is illustrated in Fig. 1 and can be more generally

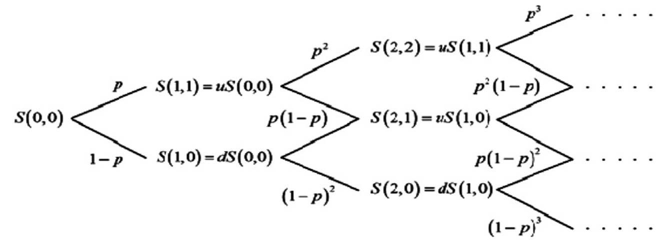

Fig. 1. Binomial lattice for a random price process. *Source*: [26].

written as follows:

$$\begin{cases} S(k+1,i+1) = uS(k,i), & \text{with probability} \quad p, \quad 0 \le k \le T \quad \text{and} \quad 0 \le i \le k \\ S(k+1,i) = dS(k,i), & \text{with probability} \quad 1-p, \quad 0 \le k \le T \quad \text{and} \quad 0 \le i \le k \end{cases}$$

where S is NRE cost T is the number of time periods, n is the number of volatility periods, k is the time period, $0 \le k \le T$, i is the number of upward NRE cost movements, $0 \le i \le k$, α is risk-free interest rate, p is the probability of a price increase, $p = (e^{\alpha} - d)/(u-d)$, u is the range of NRE cost upward movement, $u = e^{\sigma\sqrt{T/n}}$, d is the range of NRE cost downward movement, $d = 1/u = e^{-\sigma\sqrt{T/n}}$, and σ is the volatility rate of NRE price.

3.2. Model formulation

By accounting for several factors which affect the development of solar energy including uncertainty of NRE costs and learning-by-doing in solar electricity generation, a full binomial lattice can be formed covering all time steps between the valuation and expiration dates. Learning-by-doing refers to a situation in which production increases or in which labor or management accumulates experience, so that the average factor input per unit of production is reduced. This is often measured by progress rations (PR_D) which is given by 1 subtracted by the learning rate (LR_D). According to [33], the learning rate of solar power in China will reach 50% with an additional 2% of conversion efficiency by 2015. Based on price reduction of silicon materials, increase in conversion efficiency, current decline in production costs and the 2015 prediction, this study assumes 30% to be the current learning rate for solar power in China. This means that the progress ratio of solar power technology is 0.70 which implies that when production doubles, cost is reduced to 70% of the original cost, i.e., a 30% reduction. It is therefore not surprising why China has grown to become the largest PV manufacturing nation in the world. For this, we assume that the government's RE stimulus efforts lower the real cost of solar energy from 0.92 RMB/KWh to 0.644 RMB/KWh with a simple linear decline over the 10-yr period beginning 2011. Incorporating these results, the optimal policy value can be computed using a backward-induction process. Backward-ward induction is a technique where people work back from a known outcome through the series of decisions that could lead to that outcome to assist them with the decision-making process. In such a case, each node in the lattice would be a representation of possible value of the underlying at a given point in time. The valuation is then performed iteratively, starting at each of the final nodes and then working backwards through the tree towards the first node.

As noted by Siddiqui et al. [1], for technologies without prior RE deployment, there are three main types of options namely: options to abandon, expand, or fully deploy. Once deployed, the FIT policy has an expected cost savings relative to the expected cost of NRE.[5] On the one hand, if no deployment takes place, then FIT policy on the technology may continue. This not only guarantees enhanced future performance but also translates into lower RE costs and an increased probability of

[5] It should be noted that deployment is a one-time irreversible decision.

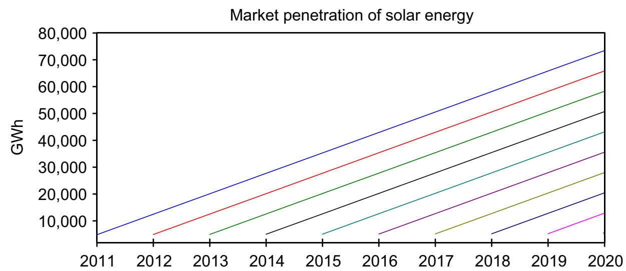

Fig. 2. Market penetration of solar energy in the Chinese fuel mix.

future deployment. The value function $W(k,i,r,j)$ recursively calculates the discounted expected future benefit of continuing RE policy with RE deployment, where k represents time period, i represents number of upward NRE cost movements, r represents number of premium expenditure increments, and j represents number of RE technologies deployed. On the other hand, the value function $V(k,i,r)$ models the cash flows associated with the three possible decisions available when the FIT policy is ongoing, i.e., abandonment, deployment, or continuation. In order to conserve space, only the value function which models the benefit of continuing RE policy with RE deployment is presented. According to Siddiqui et al. [1], the binomial lattice approach is relatively intuitive compared to the approach of Boomsma et al. [27] and explicitly models the option-pricing problem in discrete time. The value function used in the stochastic dynamic program formulation is given as:

$$\begin{aligned}W(k,i,r,j) = {} & \{[((S(k,i)+CE_{\cos\ t})-(C(k,r)^{PR_{Dk}}))X_{RE}(k,j)]-M \\ & -[(R-C(0,0))X_{RE}(k,j)]\}+\{\rho(W(k+1,i+1,r+1,j+1)) \\ & +(1-\rho)(W(k+1,i,r+1,j+1))\}\end{aligned} \quad (1)$$

where $S(k,i)$ is the NRE cost in period k given i upward NRE cost movements, $CE_{\cos t}$ is the CO_2 emission cost, $C(k,r)$ is the RE cost in period k given r increment in FIT, which has decreased from the starting value $C(0,0)$, $X_{RE}(k,j)$ is the annual RE penetration into the Chinese fuel mix in period k given j deployment of RE technologies, M is the maintenance cost after deployment, R is FIT, T is the number of periods, n is the number of volatility periods, α is the risk-free interest rate, p is the probability of a price increase, $p=(e^{\alpha}-d)/(u-d)$, u is the range of NRE cost upward movement, $u=e^{\sigma\sqrt{T/n}}$, d is the range of NRE cost downward movement, $d=1/u=e^{-\sigma\sqrt{T/n}}$, σ is the volatility rate of NRE price, σ is the volatility rate of NRE price, PR_D is the progress ratio for learning by doing, k is the time period $0\le k\le T$, i is the number of upward NRE cost movements, $0\le i\le k$, r is the number of FIT increments, $0\le r\le k$ and j is the number of RE technologies deployed, $0\le j\le k$.

Eq. (1) demonstrates that the deployment of RE technologies should invoke an immediate cost savings of $[((S(k,i)+CE_{\cos\ t})-(C(k,r)^{PR_{Dk}}))X_{RE}(k,j)]$ minus any maintenance cost M.The term $[(R-C(0,0))X_{RE}(k,j)]$ represents Chinese FIT policy cost while $\{\rho(W(k+1,i+1,r+1,j+1))+(1-\rho)(W(k+1,i,r+1,j+1))\}$ is the policy value during the policy planning lifetime which is estimated by means of the backward-induction process. For instance, $W(1,1,1,1)$ represents the optimal value of the FIT policy after one period has elapsed, there has been one upward movement in the NRE cost, one premium expenditure has been made, and the RE technologies have been deployed. In the same way, the FIT policy value function of a policy to haut development of RE after implementation of the policy for one period can be represented as $W(1,0,1,1)$. After computation of all the $W(k,i,r,j)$, the overall value of the FIT policy, $W(0,0,0,0)$, under the real options framework becomes:

$$\begin{aligned}W(0,0,0,0) = {} & \{[((S(0,0)+CE_{\cos\ t})-(C(0,0)^{PR_{Dk}}))X_{RE}(0,0)]-M \\ & -[(R-C(0,0))X_{RE}(0,0)]\} \\ & +\{\rho(W(1,1,1,1))+(1-\rho)(W(1,0,1,1))\}\end{aligned} \quad (2)$$

4. Scenario analysis and parameter estimation

In this section, we analyze the data for solar power in China. According to CNPSR (2012), the cumulated installed capacity of solar PV stood at 3.5 GW by the end of 2011. The government's target is for cumulated installed capacity is to reach not less than 50 GW by 2020. Making use of assumptions in the IEA Solar PV Roadmap (IEA 2010 m), this study estimates the electricity generation from eligible PV to be 4841.1 GWh and 73350 GWh by the end of 2011 and 2020 respectively. We point out that the model has no active competition between alternative generation technologies, so the market penetration of solar energy is predestined. We show the market penetration pattern as a family of curves in Fig. 2. As may be observed, there is a separate curve for each year in which deployment might occur. For instance, the uppermost curve shows the market penetration given the deployment of solar energy in the first possible year, 2011, reaching 73,350 GWh in 2020. Given that deployment occurs in 2011, the penetration in 2020 is 65,859 GWh, etc.[6]

To ensure a proper analysis of solar power in China, we construct three scenarios which include a base case, internalization of external costs, and variation in the level of FIT expenditures. Input parameters for the scenario analysis with related notes are given in Table 1. The next attempt will be to present and analyze each scenario.

4.1. Base case analysis

The sole purpose of this case is to analyze and quantify the benefits which could be derived from Chinese solar power development policy. As we have mentioned, the target set by the Chinese government is for installed capacity of solar to reach not less than 50 GW or 73,350 GWh of electricity generating capacity by 2020. Indeed, China has rich solar resources across its territory. According to the United Nations Environment Program's Solar and Wind Energy Resource Assessment, the annual solar radiation for most regions of China is between 4.5 and 5.0 KW per square meter per day. In some of the western parts of China, such as Qinghai, Tibet and Xinjiang, solar radiation reaches between 6.5 and 7.0 kW per square meter per day, which is similar to the radiation rates seen in the Sun Belt city of Phoenix, Arizona. Realizing such potential, fixed price of FIT for power acquisition to promote the use solar energy has been establish with two different levels of tariff corresponding to different timing of projects. On the one hand, projects approved prior to July 1, 2011, which have completed construction and have achieved commercial operation prior to December 31, 2011, are entitled to a tariff of RMB 1.15/KWh (approximately U.S. \$0.177/KWh). On another hand, projects approved after July 1, 2011 (or approved prior to that date but which could not be completed before the end of 2011) are entitled to a tariff of RMB1/KWh (approximately U.S. \$0.154/KWh). However, exceptions have been given to projects located in Tibet, which, under certain circumstances can still receive a FiT of RMB1.15/KWh. Since data on generation of solar power in each of the FIT categories could not be assessed; this study uses the average tariff (weighted by the proportion of installed capacity) of RMB 1.1/kWh. This represents a significant premium on the average rate of RMB 0.34/KWh paid to coal-fired electricity generators and are largely based on the regional 'government approved' tariffs developed between 2006 and 2008. As stated in the '2007 Medium and Long-Term Development Plan for RE in China', this paper uses 2020 as the policy planning target year to

[6] Values are based on authors' own calculations and Chinese government's solar energy targets for 2020.

Table 1
Input parameters for scenario analysis.

Variable	Description	Scenario 1	Scenario 2	Scenario 3	Notes
$S(k, i)$	Non-renewable energy cost (NRE cost)	0.24 RMB/KWh	Same as 1	Same as 1	Estimated NRE cost from weighted average coal-fired power generation cost in 2010, [34].
CE_{cost}	CO_2 emission cost	0 RMB/KWh	2.84 RMB/KWh	Same as 1 and 2	CO_2 emission factor for NRE is 842 gCO_2/KWh and 323 gCO_2/RMB (see Fig. 4). This study adopts the lower bound of CO_2 emission cost.
$C(k, r)$	Renewable Energy cost (RE cost)	0.92 RMB/KWh	Same as 1	Same as 1	Estimated RE cost from weighted average onshore wind power generation cost in 2010, [34].
$X_{RE}(k, j)$	Annual RE supply	4841.1 GWh–73,350 GWh	Same as 1	Same as 1	The annual RE penetration into the Chinese fuel mix is equivalent to the total on-grid solar power output which is 73,350 GWh in 2020 (see Fig. 1). We assume that once deployed, solar energy can only increase its penetration by a maximum of 7621 GWh annually.
M	Maintenance cost	0.20 RMB/KWh	Same as 1	Same as 1	Estimated maintenance cost after deployment of wind technologies, [34].
R	Feed-in tariff	1.1 RMB/KWh	Same as 1	1.1–2.0 RMB/KWh	Fixed average price weighted by the proportion of installed capacity, [35].
T	Number of time periods	10	Same as 1	Same as 1	Time to maturity is 10 yr, i.e. 2011–2020, which is the target year of the 2007 Medium and Long-Term Development Plan for RE in China
n	Number of volatility Periods	10	Same as 1	Same as 1	Same as the number of time periods
α	Risk-free interest rate	0.0362	Same as 1	Same as 1	Average 10-yr government bond, 2005–2012, according to the Ministry of Finance of China
p	Probability of a price Increase	0.72	Same as 1	Same as 1	$p=(e^{\alpha}-d)/(u-d)$
u	Range of NRE cost upward movement	1.08	Same as 1	Same as 1	$u=e^{\sigma}\sqrt{T/n}$
d	Range of NRE cost downward movement	0.926	Same as 1	Same as 1	$d=1/u=e^{-\sigma}\sqrt{T/n}$
σ	Volatility rate of NRE energy price	0.075	Same as 1	Same as 1	From1997 to 2009, the standard deviation of Qinhuangdao price movements has been 0.11 (Authors' own calculation based on data from China coal report). Since fuel costs represent about 68% of total electricity generation costs, [34]. We estimate the volatility of NRE to be 0.075 (0.11×0.68). We use long-run volatility because the emphasis in this analysis is on long-run price trends.
PR_D	Progress ratio for learning by doing	0.70	Same as 1	Same as 1	Using the results of solar Power See Section 3.2
k Time	period				
i	Number of upward	0–10	Same as 1	Same as 1	Same as the number of time periods

Table 2
Real options model results under scenarios 1 and 2 (billion RMB).

Scenario	Total real options value	Value of existing solar energy technologies	Value of future policy enhancement	value of policy abandonment flexibility
Base case	36.5	6.39	30.1	0.02
Internalizing external cost	2090	300.6	1789.4	0.00

assess the benefits generated by the government′s policy for solar power development.

Using the stochastic dynamic program formulation and the parameter values presented in Table 1, the optimal total policy value of Chinese solar technologies under the base case scenario is estimated to be 36.5 billion RMB. For all base case parameter values, the real option model yields a positive value and indicates that solar technologies are economic and therefore the FIT program should be continued if the current cost of electricity for the most competitive solar technology more than triples the current NRE cost of electricity of 0.24 RMB/KWh. In an attempt to give a clearer estimate of the options value added by the RE policy program rather than that of the entire technology, this gross result is disaggregated as shown in Table 2. As may be observed, the total options value is dominated by the value of enhancements to solar technologies from future FIT policy efforts, while the value of existing solar technologies which can be deployed to meet residual demand at a cost of 0.92 RMB/KWh along all price paths that lead to prices higher than this baseline including the mean trajectory, is a modest 17.5% of the total. The dominance of the value of future FIT enhancements policy provides the result of primary interest and demonstrates the significance of the Chinese RE program for solar power. Finally, the results show that the value of the abandonment option is insignificant. This means that the flexibility to abandon the FIT program is not valuable and as such, continuing the program should be mandatory. The value of this option is derived from protecting against downside risk, i.e., if NRE cost becomes extremely low and the potential for RE deployment is almost foreclosed, then it is cheaper to abandon the FIT program completely. However, in China where NRE cost does not reflect externalities and given low NRE cost volatility, there is not much chance of a downside (or upside), so the abandonment option will never be exercised.

To conclude discussion on the base case scenario, it would be necessary to point out that considering the annual FIT expenditures paid to solar over 10 yr, the total real options value of 36.5 billion RMB might seem a bit low, especially given the fact that the value captured by this result represents the full options value of solar technology available for deployment throughout the forecast period. However, this should not be very surprising especially given that the above analysis did not account for the hidden costs embedded in NRE. This should not be taken for granted considering that China is currently the world's largest carbon emitter. Hence, the next scenario explores the impact on the overall policy value when the cost of fossil fuel electricity reflects the CO_2 emissions cost.

4.2. Internalization of external costs

An external cost or externality is a cost that is not transmitted through prices and is incurred by a party who was not involved in

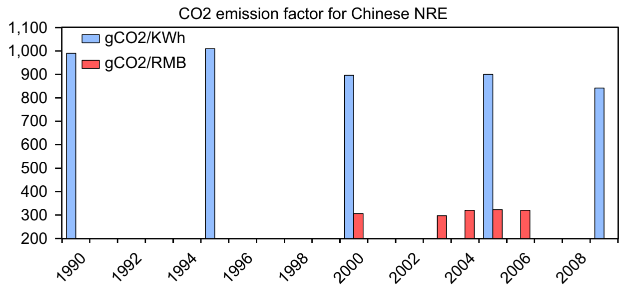

Fig. 3. CO_2 emission factor for Chinese NRE (gCO2/KWh and gCO2/RMB). *Source*: [36,37].

the process causing the cost. For example, a power station that causes CO_2 emissions imposes costs on the whole society ranging from the degradation of the environment, with impacts on water and soil quality and human health. Further damages and costs come with combustion of fossil fuels, in terms of air quality and climate impacts, and with waste disposal. In this study, we define external cost as the CO_2 emission cost which we calculate using the indicators gCO_2/KWh and gCO_2/GDP as shown in Fig. 3. At 840 gCO_2/kWh in 2009, the average CO_2 emission factor for NRE is 36 percent higher than in non-OECD countries. Since the current method of estimating the cost of generating electricity with coal-fired power for China excludes social costs such as GHG emissions, especially CO_2, this has lowered the cost of coal-fired power and has caused over-consumption of NRE and high electricity costs for RE. As was earlier noted, the Chinese government through its 12th Five-Year Plan has committed to reducing carbon emission per unit of GDP by 17% and 40%–45% by 2015 and 2020 respectively compared to the 2005 levels, with the development of RE as one of the key means of achieving this goal. Thus, it becomes fully justifiable to examine the appropriateness of the RE development policy for solar with internalized CO_2 emission costs.

A scenario in which external costs are internalized demonstrates significant improvement in the overall policy value. As may be observed from Table 2, the total options value overwhelmingly increases to 2090 billion RMB and is completely intuitive, i.e., internalizing external costs leads to higher NRE costs which in turn increases the options value of RE technologies. As NRE costs increase, the contribution of existing RE technologies to the total real options value also increases (300.6 billion RMB). This is because this component measures the difference between the NRE cost and the RE cost. As fossil fuels get more expensive, this difference increases, thereby raising the value of the existing RE technologies. Supportive of the results under the base case scenario, we also see that the total options value is dominated by the value of future FIT effort. Indeed, our findings do not only give policymakers incentive to continue funding but bring new insights into the literature both in terms of the options behavior and Chinese energy policy. Finally, the incremental options value of the abandonment option is insignificant as predicted. Interestingly, it too varies positively with the internalizing of external costs.

In summary, the appropriateness of Chinese RE policy for solar power becomes more appealing when external costs are transmitted through the prices of NRE. This result should be interesting since one of the primary objectives of the Chinese RE program is to reduce carbon emissions. To evaluate the strategic role of solar power, it is important to note that if the mitigation goal of a 40%–45% reduction by 2020 were to be achieved, gCO_2/KWh would decrease to 463.1–505.2 gCO_2/KWh. In fact, given the CO_2 emissions factor for NRE to be 842 gCO_2/KWh, this study hypothesizes that with the likelihood of RE to replace NRE, solar power use in China can potentially reduce CO_2 emissions by approximately 61760700 tCO_2 or reduce the emission factor to 831 gCO_2/KWh by 2020. This constitutes about 1.3% emission reduction compare to the 2005 level and highlights the significant role of solar power in China's emission targets. In the next scenario, an attempt is made to examine whether the premium for developing wind power provides an adequate economic incentive.

4.3. Variation of FIT expenditures

Under scenarios 1 and 2, we have shown that, given our parameter assumptions, solar technologies provide positive value to China from a market-based perspective. We now move on to experimenting with the level of FIT rate. Although high FIT would increase the incentive for investment by private enterprises, it would also require increased government funding which translates into fiscal expenditure, and negatively impacts the overall policy value. The objective of this scenario is to use the real options formulation to examine the effect on the overall policy value when the current average FIT rate, *R*, increases gradually from 1.1 RMB/KWh to 2.0 RMB/KWh. One must not forget that solar power FIT in China has witnessed some policy changes. In the past, FITs for solar power were based on 'government guided' prices, which evolved year-by-year as competitive bidding for solar power capacity resulted in standardized or 'approved' prices, generally on a province-by-province basis. However, in July 2011, a new FIT regime was established for solar power. The question under examination here is whether an average tariff of 1.1 RMB/KWh represents the optimal. The results of the options analysis on varying the level of ongoing FIT yields as presented in Fig. 4 show that increased FIT does indeed payoff. At a deployment rate of 7621 GWh/yr once switchover is completed, the optimal annual rate of FIT is approximately 1.5 RMB/KWh and 1.7 RMB/KWh with and without internalization of external costs respectively. At these funding levels, the present value of the solar energy technologies, net of FIT, climbs from 2090 billion RMB to

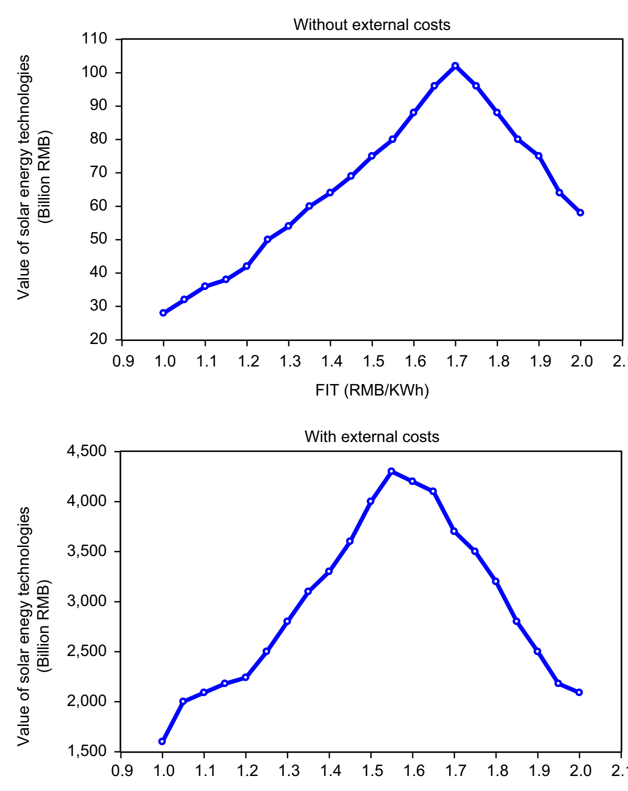

Fig. 4. Value of RE technologies with and without external costs as a function of ongoing FIT.

4300 billion RMB and 36.5 billion RMB to 102 billion RMB with and without external costs respectively. On the contrary, any expenditure levels beyond these optimal do not increase investment efficiency but only lead to increased government spending towards the development of RE resulting in another fiscal expenditure that negatively impacts the overall policy value. This analysis not only lends support to the Renewable Energy and Energy Efficiency Policy of China which calls for government support for renewables, but also suggests that the government expenditures on FIT should be raised to between 1.5 RMB/KWh and 1.7 RMB/KWh while considering policies that focus on benefit-maximization.

5. Concluding remarks

In this study, we have attempted to quantify the value of Chinese RE program by applying real options theory, which draws upon insights from financial markets in order to value these RE benefits for solar power generation. The modeling approach adopted in this study more correctly represents the actual RE development climate than previous models that assigned a fixed value to technical risk or that considered only a single factor in RE technical improvements. Our calculation of the optimal FIT policy solution reveals solar energy technologies in China to be economically attractive, thus providing a good alternative for China's energy future irrespective of whether external costs are internalized or not, with the incremental option value of a 10-year FIT effort adding to that already significant value. The option value of FIT abandonment, however, is relatively modest. In addition, we find the options value to be significantly greater when external costs are internalized. This provides insights that solar energy technologies in China hold a significant amount of value that cannot be detected when the hidden costs of NRE are not reflected through prices. Hence, in order to adequately value these technologies and the benefits of continued FIT spending would require accounting for external costs. Further, the study also found that the optimal rates of FIT which ensures an investment incentive with minimal government expenditure is approximately 1.5 RMB/KWh and 1.7 RMB/KWh with and without internalization of external costs respectively. Any government expenditure above the optimal only leads to increased government spending towards the development of solar energy resulting in another fiscal expenditure that negatively impacts the overall option value. Hence, the contribution of this study extends to the literature on higher FIT impacts and external costs policies. It is necessary also to underscore the importance of the Chinese government policies that focus on increasing the installed capacity of solar power generation within the context of the learning effect inherent in Chinese solar technologies. The findings of this study turn out to be quite interesting and bring new insights into the literature both in terms of the options behavior and Chinese energy policy.

We must not forget to mention that while our estimates are a function of the selected parameter values which are subject to debate, we still strongly feel that our estimates of solar technology value have been conservative. Nevertheless, despite the contribution of this study, there are also some limitations that should be pointed out. First, full FIT timing flexibility and technical risk are not considered to keep the real options solution method as transparent as possible. Second, the model framework in this study assumes that that once RE technology is deployed or FIT policy abandoned, no further decisions can be made. Third, the average FIT value is used, owing to the unavailable of data. Finally, the model does not consider the possibility of step changes in the underlying cost of NRE that might, for example, be caused by stringent carbon regulations. Therefore, resolving the above limitations appears to be a viable avenue for further research and model improvement. For a more policy-relevant angle, future effort would also steer the focus of this paper towards an assessment of the limitations to R&D funding for solar energy technologies in China.

Acknowledgements

The paper is supported by Newhuadu Business School Research Fund, the China Sustainable Energy Program (G-1305-18257), National Social Science Foundation of China (Grant No.12&ZD059), and Ministry of Education (Grant No. 10GBJ013).

References

[1] Siddiqui AS, Marnay C, Wiser RH. Real options valuation of US federal renewable energy research, development, demonstration, and deployment. Energy Policy 2007;35:265–79.
[2] Ma H, Les O, John G, Wen L. A survey of China's renewable energy economy. Renewable and Sustainable Energy Reviews 2010;14:438–45.
[3] Wesseh Jr PK, Zoumara B. Causal independence between energy consumption and economic growth in Liberia: evidence from a non-parametric bootstrapped causality test. Energy Policy 2012;50:518–27.
[4] Wesseh Jr PK, Lin B, Owusu Appiah M. Delving into Liberia's energy economy: technical change, inter-factor and inter-fuel substitution. Renewable and Sustainable Energy Reviews 2013;24:122–30.
[5] Fisher I. The rate of interest: its nature, determination, and relation to economic phenomena. New York: Macmillan; 1907.
[6] Fisher I. The theory of interest. New York: Macmillan; 1930.
[7] Dixit AK, Pindyck RS. The options approach to capital investment. Harvard Business Review 1995;73:105–15.
[8] Tseng CL, Barz G. Short-term generation asset valuation: a real options approach. Operations Research 2002;50:297–310.
[9] Deng S-J, Oren SS. Incorporating operational characteristics and start-up costs in option-based valuation of power generation capacity. Probability in the Engineering and Informational Sciences 2003;17:155–81.
[10] Lewis N, Enke D, Spurlock D. Valuation for the strategic management of research and development projects: the deferral option. Engineering Management Journal 2004;16:36–48.
[11] Fernandes B, Cunha J, Ferreira P. The use of real options approach in energy sector investments. Renewable and Sustainable Energy Reviews 2011;15:4491–7.
[12] Trigeorgis L. Real option: managerial flexibility and strategy, resource allocation. Second ed.. Westport: Parager Publisher; 1997.
[13] Black F, Scholes M. The pricing of options and corporate liabilities. Journal of Political Economy 1973;81:637–54.
[14] Merton RC. Theory of rational option pricing. The Bell Journal of Economics and Management Science 1973:141–83.
[15] Myers SC. Determinants of corporate borrowing. Journal of Financial Economics 1977;5:147–75.
[16] Madlener R, Stoverink S. Power plants investments in the Turkish electricity sector: a real options approach taking into account market liberalization. Applied Energy 2012;97:124–34.
[17] Venetsanos K, Angelopoulou P, Tsoutsos T. Renewable energy sources project appraisal under uncertainty—the case of wind energy exploitation within a changing energy market environment. Energy Policy 2002;30:293–307.
[18] Kjaerland F. A real option analysis of investments in hydropower—the case of Norway. Energy Policy 2007;35:5901–8.
[19] Dixit AK, Pindyck RS. Investment under uncertainty. Princeton, NJ: Princeton University Press; 1994.
[20] Bockman T, Fleten S, Juliussen E, Langhammer H, Revdal I. Investment timing and optimal capacity choice for small hydropower projects. European Journal of Operational Research 2008;190:255–67.
[21] Munoz~ JI, Contreras J, Caamano~ J, Correia PF. Risk assessment of wind power generation project investments based on real options. In: IEEE Bucharest power tech. conference; 2009.
[22] Martínez-Cesena~ EA, Mutale J. Application of an advanced real options approach for renewable energy generation projects planning. Renewable and Sustainable Energy Reviews 2011;15:2087–94.
[23] Yu W, Sheble G, Lopes J, Matos M. Valuation of switchable tariff for wind energy. Electric Power Systems Research 2006;76:382–8.
[24] Kumbaroglu G, Madlener R, Demirel M. A real options evaluation model for the diffusion prospects of new renewable power generation technologies. Energy Economics 2008;30:1882–908.
[25] Siddiqui A, Fleten S-E. How to proceed with competing alternative energy tech nologies: a real options analysis. Energy Economics 2010;32:817–30.
[26] Lee S-C, Shih L-H. Renewable energy policy evaluation using real option model —the case of Taiwan. Energy Economics 2010;32:S67–78.
[27] Boomsma Tk Meade N, Fleten S-E. Renewable energy investments under different support schemes: a real options approach. European Journal of Operational Research 2012;220:225–37.

[28] Davis G, Owens B. Optimizing the level of renewable electric R&D expenditures using real options analysis. Energy Policy 2003;31:1589–608.
[29] Zhang P, Yang Y, Shi J, et al. Opportunities and challenges for renewable energy policy in China. Renewable and Sustainable Energy Reviews 2009;13:439–49.
[30] REN21. Recommendations for Improving the Effectiveness of Renewable Energy Policies in China. 〈http://www.ren21.net/news/news38.aspS〉 [retrieved 12.11.09].
[31] Lin B, Wesseh Jr PK. What causes price volatility and regime shifts in the natural gas market. Energy 2013;55:553–63.
[32] Lin B, Jiang Z. Estimates of energy subsidies in China and impact of energy subsidy reform. Energy Economics 2011;33:273–83.
[33] China National Photovoltaics Status Report; 2012.
[34] IEA. Projected Costs of Generating Electricity; 2010.
[35] National Development and Reform Commission of China.
[36] China Wind Energy Association; 2011.
[37] International Energy Agency; 2009b.